THE DESIGN AND CONSTRUCTION OF THE NEW WATERWAY STORM SURGE BARRIER IN THE NETHERLANDS

technical and contractual implications

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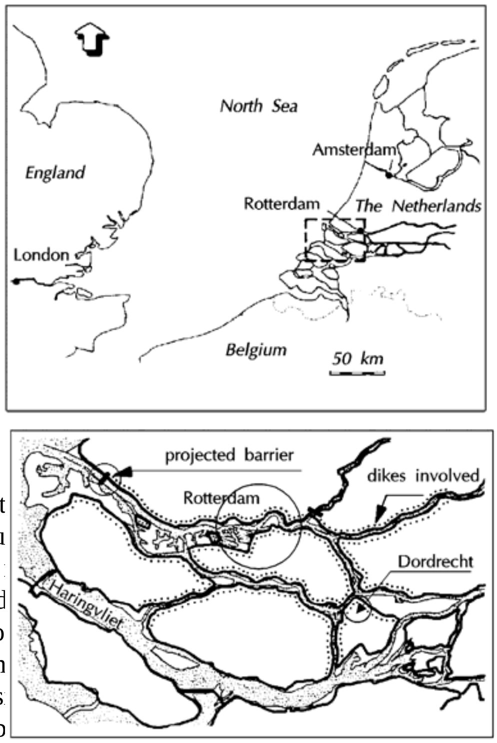
1. Introduction

For the south-western part of the Netherlands the safety against flooding is prescribed by the Delta Act. This Act was made after the severe flood disaster in 1953 when nearly 2000 people drowned. The Delta Act prescribed the shortening of the coastline by closing off many of the existing tidal inlets and the strengthening of the remaining dikes. It also proclaimed that the New Waterway and the Western Scheldt had to remain open because of the harbours of Rotterdam and Antwerp. The dikes along these waterways and along the waterways connected with it had to be strengthened. In 1985, a reexamination of the design water levels led to even higher values than those considered in the Delta Act. This meant another 200 kilometres strengthening of river dikes, including costly protection works in densely populated or infrastructurally complicated areas. See Figs. 1 and 2 for the project area.

The work involved with the strengthening of dikes would not be finished before the year 2020. Therefore, in 1987, the Dutch Government initiated a study to reconsider a movable storm surge barrier in the New Waterway. To be feasible the barrier had to meet several goals. The most important ones being:

* a closing frequency of the barrier less then once every 10 years now, and once every 5 years after 50 years of operation (due to 25 cm sea level rise),
* a prescribed reduction of design water levels (a local water lever with a fixed frequency of exceedance) at two representative locations, the cities of Rotterdam and Dordrecht.



Figs. 1 and 2: Project area

The prescribed maximum closing frequency shows the strong emphasis on the open character of the Rotterdam harbour. Also ot highly appreciated the economic importance of the Rotterdam harbou After an extensive study, the feasibility and the effectiveness of a consortia were asked to make predesigns for the barrier. At the end sector gate barrier designed by the B.M.K. Barrier Design and Co contract was granted. The BMK barrier turned out to be an econom which the dikes had to be improved. In concordance with this decis also after the barrier is completed and is operating, dikes will b strengthened, although to a much lesser extent. This was taken into a the barrier.
In a previous contribution [1] the preconditions for the barrier design were briefly described. The three main predesigns were

also outlined in that contribution, among them the BMK barrier. At that time the final choice had not been made yet.
This contribution concentrates on the next phases. It describes the tender philosophy and the procedure of selecting the final barrier design (par. 3), the design-and-construct contract with all its specific problems and advantages (par. 4), the details of the current barrier-design which is slightly different from the original one (par. 5) and also a description of the design process itself (par. 6), the hydrodynamic problems that strongly influenced the final geometry of the barrier (par. 7) and, last but not least, the management of the design process (par. 8). Finally some conclusions will be drawn. However, first the project area and its hydraulic features are described to get a better understanding of the preconditions imposed on the barrier-design.

2. Project description and hydraulic system

The project area covers the lower river reaches in the south-western part of the Netherlands, as shown in Figures 1 and 2. Figure 2 represents the Rhine and Meuse Delta network, in which water levels will be influenced by operating a storm-surge barrier in the New Waterway. Combined with the dikes along the river branches the barrier will provide safety against flooding.

In Figure 3 the hydraulic system is shown in a schematic form. Basically, there are two river branches with several connections. The southern branch runs into the large Haringvliet estuary. This estuary is separated from the sea by a barrage with large discharge sluices. These sluices are closed during high tide to prevent sea water from entering the delta region. During low tide they are closed only when the river discharge is low. In this way, the water is forced to discharge through the northern branches, to stop the salt intrusion from the sea.
The northern branch runs freely into the sea through the city of Rotterdam and the New Waterway. Tidal movements and storm surges enter the system through this northern branch. Close to the river mouth the water level is determined by the tidal movement and the storm surge. Travelling upstream the incoming wave is damped and the phase is shifted. The water levels in this intermediate region are determined by both sea-water levels and river discharge.

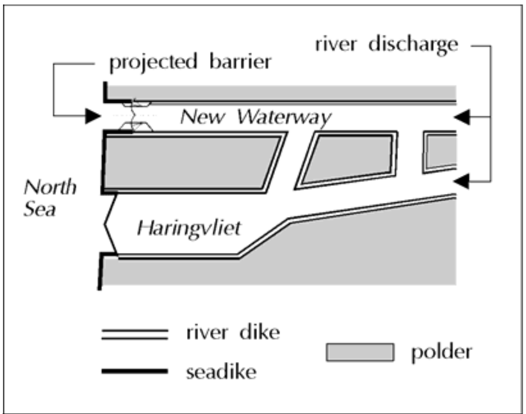


Fig.3: Hydraulic system

In the hydraulic system the effect of the barrier on water levels is twofold. One effect is the reduction of water levels because the storm surges cannot enter the system any more. On the other hand, there is an increase of water levels because of the accumulation of river water behind the barrier.
To calculate the total balance of effects, the hydraulic system has been modelled by a mathematical open-channel network model. The schematization of the system is conform Figure 2 and consists of about 200 branches and nodes. This model has been in use for a long time for prediction of water levels on a daily basis and to determine design water levels for the situation without a barrier. To study the effects of a barrier, the model has been extended with a weir structure. Boundary conditions for the model are the river discharge and the combined effect of tide and storm surge.
Due to shipping, strict requirements have been imposed upon the barrier-design. The most important ones being the maximum closing frequency of the barrier and the restriction of operation-induced translation waves within specified limits. Also the space required for the passage of ships is prescribed. The minimum width above Mean Sea Level (MSL) -10 m is 360 m and the minimum sill depth is MSL -17 m.
Since the performance of the barrier is measured in statistical quantities (e.g., design water level reduction and closing frequency) probabilistic calculations are necessary. The hydraulic model is used to translate boundary conditions into local water levels. The probability density functions of the boundary conditions are used to derive the probability of exceedance of the local water levels by a probabilistic full integration method. In the probabilistic calculations also the reliability of the barrier is taken into account. The reliability of the barrier concerns the probability that the barrier is not closed due to:
- inaccurate water level prediction,

- human or technical errors,
- collapse (insufficient strength).

The performance of the barrier is also influenced by the characteristics of the barrier and its operation, e.g., moment and duration of both closing and opening.

Since design water levels are a Governmental responsibility, it seems logical to set technical requirements to the characteristics of the barrier that influence the design water levels. On the other hand the contractor should have as much freedom of design as possible.

The technical requirements have been established by a sensitivity analysis for the barrier performance. In this analysis the influence of the reliability, the characteristics and the operation (strategy) of the barrier is established. Aiming for adequate performance an optimum strategy and realistic reliability targets (especially with human errors involved) can be described.

The optimum strategy is:

- closure at a sea water level of MSL +2.00 m for river discharges less than 6000 m^3/s and at slack water for higher discharges,
- opening at equal water levels on both sides of the barrier,
- discharging water through the barrier between two high waters at sea (i.e. when water levels on the riverside of the barrier are higher than on the seaside) with a minimum wet surface of 1000 m^2 net that has to be realised within 20 minutes.

The reliability targets are:

- probability of not closing due to human or technical errors less than 10^{-3} on demand,
- probability of collapse less than 10^{-6} in any year,
- probability of not opening due to human or technical errors less than 10^{-4} on demand.

For the barrier-characteristics limits have been targeted. Within these limits the barrier performs well. The targeted barrier-characteristics are:

- full closure in less than 2.5 hours and 80% closed within 1.5 hours,
- full opening in less than 2.5 hours and 20% open within 1 hour,
- average retaining level MSL +5 m,
- leakage area through the closed barrier less than 100 m^2 net,
- up to 4000 m^3/s river discharge, it is allowed to reduce the hydraulic head over the barrier by letting in water through a limited opening in the barrier.

If the contractor satisfies the technical requirements, then the design water levels are sufficiently reduced. Since it is not described how to fulfil the requirements, this procedure gives the contractor maximum freedom of design.

3. Basic tender philosophy and selection procedure

The construction of the Eastern Scheldt storm surge barrier (1978-1986) induced considerable negative publicity because of its budget overruns (approx. 30% in total). Therefore, the intention was to realise the storm-surge barrier in the New Waterway following the basic principles of market mechanism philosophy. The market (designer-contractors) should be given the opportunity to show their skills as opposed to the usual designer-role of the Rijkswaterstaat of the Dutch Ministry of Public Works. Moreover, this philosophy was enhanced by political aims to diminish the activities of governmental bodies in favour of a stronger market approach. The result was that a "design and construct contract" was put out to tender according to European rule. This tender philosophy was new to the Rijkswaterstaat. It should result in a project where the owner would surely get:

- a storm-surge barrier for a predetermined price,
- value for money through competitive designing and bidding by Europe's most outstanding designers/contractors,
- a technical state-of-the-art work that complies with the specifications,
- design and construction in one hand.

Therefore, different European contractor consortia were invited to:

- draw up a preliminary design of a storm-surge barrier, based on a limited number of rather abstract technical (operational - and design boundary conditions) requirements,
- present a lump sum price for the design and construction of the barrier, including maintenance over a period of 5 years.

To do this the contractors were given a period of three months. The technical requirements were intentionally

formulated on a high level of abstraction to encourage innovative, bright and economical solutions.
Initially 6 contractor consortia applied for the tender. After a first selection (considering the contractor's design experience), 5 consortia were invited to prepare the conceptual design and to offer a fixed price within 3 months.
During these 3 months the Rijkswaterstaat prepared the technical requirements for the next phase of the selection. This resulted in the basic requirements for reliability, operational management and characteristics of the barrier as described in the previous section.
To select the most appropriate technical and financial solution Rijkswaterstaat felt the need to acquire sufficient knowledge of the specific "snags" in the design process. Therefore, they elaborated a number of conceptual designs of the barrier to such a level that all major problem areas and other areas of interest were understood. This work was carried out by a team of specialists during the same three months in which the contractors prepared their design and bid offer. This resulted in a clear understanding of what was possible and what was not. Reliability and maintainability were the key criteria to select the designs on, besides of course cost and design quality.
After the three-month period, the 5 barrier-designs were evaluated. In Fig. 4 the barriers are shown schematically. Based on the criteria mentioned above the sector gate and the segment door were chosen for further competition. An important difference between the two designs is that the sector gate is floated into the river and then sunk to the bottom and the segment door is ridden into the river. In this final phase of the competition the two consortia did hydraulic model testing on their designs at the Delft Hydraulics Laboratory to eliminate all remaining uncertainties. The Rijkswaterstaat monitored these testings.
Then the consortia refined their bids. After a technical evaluation, the Rijkswaterstaat finally selected the BMK sector gate on the basis of costs. The BMK consortium was granted the contract amounting to approximately 700 million guilders in total.
The main technical reason for selecting the BMK design is the simplicity of the technical concept. Moreover, the structure is easy to maintain, mainly in dry conditions with only limited parts remaining under water.

The selection procedure almost took one year. The use of a step-by-step selection procedure guaranteed a continuing market mechanism throughout the procedure and induced the best quality.

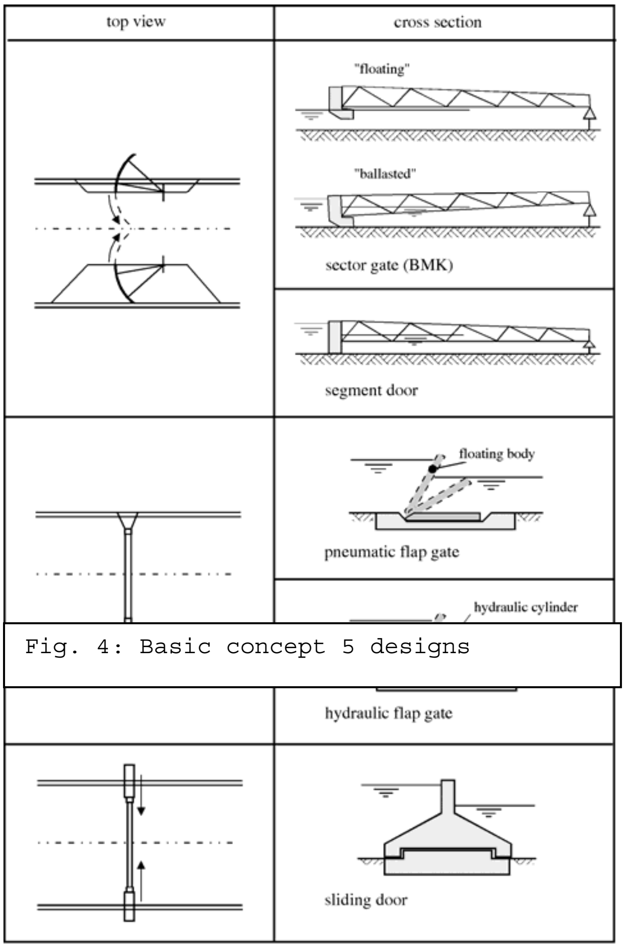


Fig. 4: Basic concept 5 designs

4. Contract considerations

The contract involves both the total design and the construction of the storm surge barrier. Besides, the contractor is responsible for the maintenance of the barrier during the first five years of operation. This combination of responsibilities (risks) should give the contractor an incentive to search for an overall economically sound solution for all design problems.
However, the New Waterway storm surge barrier is a structure to defend one of the most densely populated parts of the Netherlands against floods. Defending the country against floods is one of the responsibilities of the government which of course cannot be transferred to a private organisation. If the structure would fail under design conditions this would mean a major national disaster. Moreover, it is hardly possible from an economical point of view to have the design insured against risks of this magnitude. Therefore the Dutch government takes over the risks of faulty design work on delivery.
Another problem to bear in mind is the fact that the design loads (with very low frequencies of occurrence) on the barrier are not likely to occur. It is thus impossible to run tests on delivery to determine whether the barrier meets

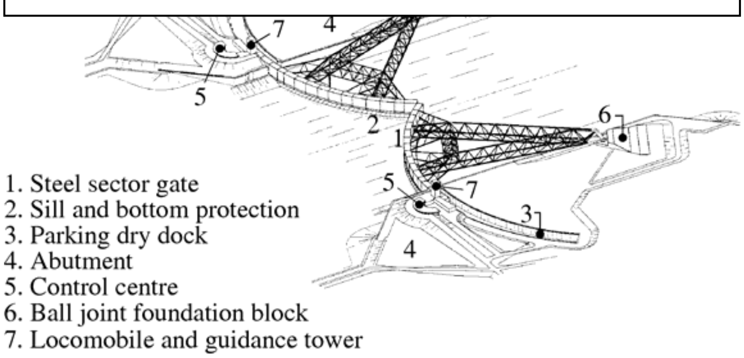
its basic requirements.
The three considerations mentioned above are directive to the role the owner should play in the process. It has therefore been decided that a team of experts from the Rijkswaterstaat would monitor the design and construction. To enforce this role, the contract contains a so-called "procedure of acceptance". Each part of the design or construction that has influence on the barrier's performance has to be accepted by the team of the Rijkswaterstaat. If no acceptance is given, the contractor is not allowed to release that particular part for further engineering or construction.
To ensure a clear phase-to-phase working procedure, the contract states that a number of documents have to be produced in a certain order. In this way fast tracking is eliminated for most of the work. Again, acceptance of these documents by the owner is necessary in order to continue parts of the project. Successively, basic design documents, engineering documents, specification documents, quality-control documents and construction plans have to be produced. All of this work is done following the requirements imposed by the ISO-9000 standards. These quality-assurance standards are rather new to the practice of civil engineering in the Netherlands. Subsequently, all parties involved (both owner and contractor(s)) had to put a lot of energy into the design and the implementation of quality assurance (QA) and quality control (QC) procedures and also to create and maintain a quality-minded workforce.

This procedure has now been followed for about three years. The experiences have been mostly positive. In the beginning of the project differences had to be overcome, mainly concerning the new roles of both contractor and Rijkswaterstaat. The contractor was used to building and now had to include designing, the Rijkswaterstaat was used to designing and now had to refrain from doing this. The following exaggeration will further clarify this: the staff engineers of Rijkswaterstaat felt that they were the only really experienced designers; the contractor engineers felt that they had to go through the ordeal of some design work before the real job, being the construction, could start. Rather soon after some initial "misunderstandings" both parties found out that the only way to fulfil the assignment was by working together as the complementary components of a team and to respect one another.

5. Description of the final design and barrier operation

The lay-out of the sector gate barrier is shown in fig 5. On each side of the channel an abutment is constructed between groynes. As such, the space available to shipping and water flow remains virtually unaltered.
Inshore of the abutment, a steel sector gate is parked in a dry dock. A sector gate consists of a circular shaped retaining wall which is connected to a hinge point by means of two steel truss works. Due to the circular shape, the rotation of the sector gate is hardly influenced by currents or hydraulic head.
Therefore, the traction of the sector gate can be simple and small, especially because the gates are floating during motion. As such, the motion of the gates is similar to the motion of a ship.
The traction consists of a traction work -the locomobile- which generates the horizontal force. The traction of the locomobile is transferred to a rail construction on top of the gate. Thus the locomobile rides on top of the retaining wall. While the locomobile remains stationary the gate moves horizontally. As shown in fig 6, the connection between the locomobile and the support near the dock must allow a vertical motion, while a horizontal displacement is prevented. Once in position, the floating doors are ballasted with water and thus sunk to the bottom.
In immersed position the sector gate rests on a sill consisting of large concrete blocks. On both sides of the sill a conventional granular scour protection is situated. The structural integrity and dimensions of the barrier are largely influenced by the hydraulic head over the barrier.

Fig. 5: Lay-out BMK sector gate



The concept of the barrier is, however, mainly determined by the strict requirements concerning obstruction to

shipping during construction and maintenance of the barrier.
The barrier has to be built to last for 100 years. In its operational lifetime, closures of the barrier are expected to occur once or twice in ten years.
The management of the structure focuses on inspection and maintenance because, during its operational lifetime, closure is expected to occur only once or twice in 10 years. Therefore a dock was used to store the gates when not operational. The dock can be set dry to achieve maximum accessibility of all vital components. As such, maintenance of the gates is as simple as the maintenance of a ship. Moreover, during construction the dock is used to assemble the prefabricated sections of the gate.
Construction and maintenance of the steel truss works can be carried out onshore, thus anticipating the requirements related to the prevention of environmental pollution. The back-bone of the structure is the hinge. Due to the ship-like behaviour, the hinge must allow rotation in all directions. Therefore a ball joint construction was used. This rotation can even occur under the ultimate loading condition as a result of large waves. Due to the large dimensions, the load caused by the hydraulic head can mount up to 370 MN for each of the gates. The ball joint transfers this large force to the sub soil by means of a concrete foundation structure which is situated inshore of the abutment on a highly compacted sand-fill. This is shown in Fig 7. The abutment consists of a sheet-pile wall (combiwall type) with a sand-fill. Apart from the gates and the locomobiles, the abutment comprises buildings for the operation team and the power supply. The abutment also protects the vital parts of the barrier against the large colliding forces from shipping accidents.

A global outline of an anticipated barrier operation can be described as follows:

- Initially the barrier is at rest in the dock; the barrier control centre is unmanned, but the automatic control system is alert.
- The Storm Surge Warning System predicts a storm surge level that exceeds the critical level.
- The crew of the barrier (decision team and operators) is warned by the automatic control system; if the decision team is not able to reach the barrier in time the automatic system is able to continue unmanned; it will only ask for authorization of crucial decisions.
- Preparations are started (start of energy generators and filling of docks).
- The ship-traffic is stopped 2 hours before closing the storm surge barrier.
- The dock-doors are opened (20 minutes).
- The automatic control system asks for authorization of the actual closure.
- The floating barrier is driven out into the river by the horizontal moving system (30 minutes).
- The valves are opened and the barrier immerses (120 minutes).
- The barrier rests on the sill with approximately 45 MN pre-tension.
- The moment of equal water levels at the upstream and downstream side of the barrier is predicted.
- Some ballast tanks are emptied to reduce the vertical pre-tension to zero (45-120 minutes).
- When the water levels on both sides of the barrier are equal, the barrier is floated by emptying the ballast tanks (120 minutes).
- The barrier is driven into the docks (30 minutes).
- The dock-doors are closed (20 minutes) and the dock water level is lowered till the gate rests on the dock floor (supports).
- The operation ends by demobilisation.

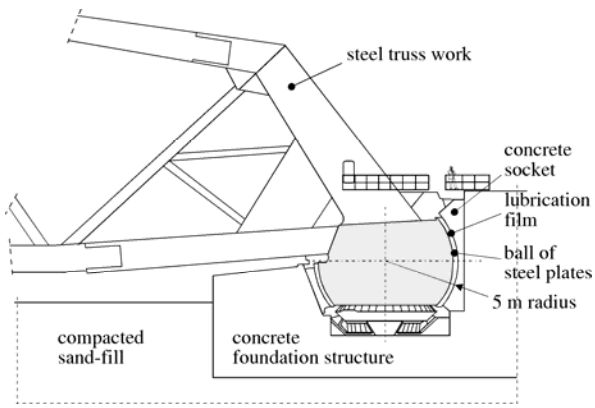
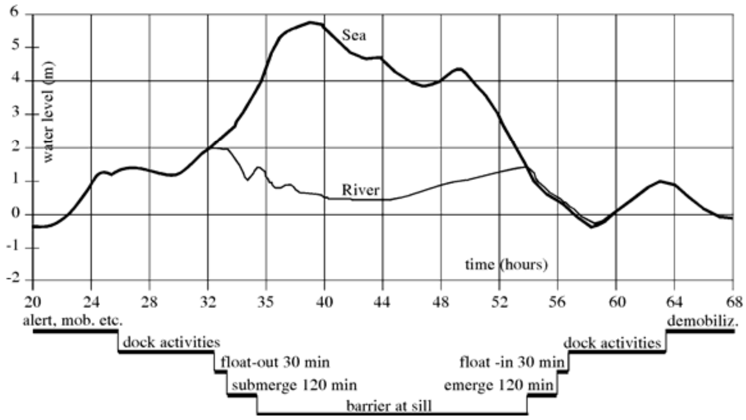
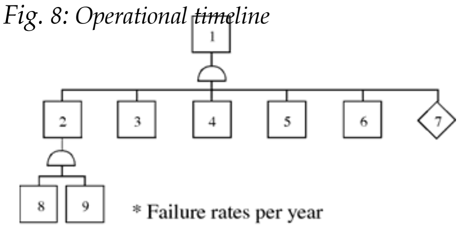


Fig. 7: Cross-section ball joint



In Fig. 8 the operational timeline of the barrier is illustrated. Together with the water levels on both sides of the barrier the most important activities are shown.

Fig. 8: Operational timeline



1 =	Barrier fails	(9.1 E-7)
2 =	Steel construction fails	(6.1 E-7)
3 =	Hinge construction fails	(2.2 E-7)
4 =	Threshold construction fails	(7.3 E-8)
5 =	Sheet pile walls fails	(-)
6 =	Seadikes fail	(1.0 E-8)
7 =	Miscellaneous causes	(-)
8 =	Doors fail	(2.1 E-7)
9 =	Arms fail	(4.0 E-7)

6. Required performance of the storm surge barrier and how to deal with it

Required Performance

The required performance of the storm surge barrier can roughly be divided in two sets of requirements: (1) functional requirements describing the operational use of the storm surge barrier and (2) given the operational use, the overall performance.

Functional requirements

In order to reduce the water levels in the hinterland adequately, barrier-characteristics are defined (see par. 2). The most relevant characteristics are:

- closing time not more than 2 1/2 hour;
- opening time not more than 2 1/2 hour;
- opening speed initially more than 8 m/hour (related to the requirement to discharge water whenever the sea water level is lower than the river water level);
- operation-induced translation waves must be controlled within specified limits.

These requirements form the basis for the design of the horizontal and vertical moving system. To be able to verify and dimension the systems, several simulation programs, including hydraulic models, have been developed.

Overall performance

For the storm surge barrier, when operating according to the functional requirements in the specified environment, overall performance requirements were assessed for the relevant utilisation phases:

- probability of not closing: 10^{-3} on demand
- probability of collapsing: 10^{-6} per year
- probability of not opening: 10^{-4} on demand

The probability of not closing can be divided into three contributing parts:

- probability of human failure during closing operation : 9.10^{-4}
- probability of ship-collision prior to closing operation : 8.10^{-5}
- probability of technical failure during closing operation : 2.10^{-5}

Lifetime

The required life-time of the barrier is 100 years. Parts of the barrier that are practically irreplaceable should be designed for this life-time. Therefore special attention had to be paid to conservation, cathodic protection, concrete and monitoring.

How to deal with the performance requirements

Obviously the above requirements cannot be used for design without further elaboration. In order to decompose the abstract requirements in appropriate requirements for design work, three basic analyses have been performed: (1) risk analyses to transform the overall failure requirements into failure requirements for (sub-)systems, (2) human failure analysis to determine the influence of human intervention on operations and (3) analysis of ship collision.

Risk-analysis

The defined probabilities of failure for the three relevant phases have been elaborated with fault-tree techniques. In that way, all possible failures at elementary level can be summarized systematically in order to determine the overall failure. In fig 9 this is illustrated for the case of barrier collapse.

Each elementary failure has its own quantitative contribution to the overall failure. This contribution was distributed initially by the design manager using both technical and economical criteria. In principle expensive or

difficult sub-systems will have a large contribution, cheap and relatively simple sub-systems will have a small contribution.
In the ideal situation the distribution of sub-system failure contribution to the overall failure of the system is interactively assessed. In practice the initially established distribution was hardly changed.
Systems like the ballasting-system or the horizontal moving system were analyzed by a failure mode and effect analysis which resulted in the probability of failure of this system. If the probability of failure exceeded the maximum allowed contribution, redundancy or alternative solutions were considered. For some cases the allowed contribution had to be enlarged at the expense of other sub-systems of the barrier.
A full probabilistic design approach was used to establish the dimensions of the sub-systems of the barrier. For this approach it was necessary to determine the probability density functions of both loads and resistance.
The most important step in the probabilistic approach is the assessment of the loads induced by the use of the barrier in the environment during storm surges. Therefore the lower Rhine delta was modelled by a mathematical open-channel network model and by full integration, the probability density functions of relevant loads were established. The following environmental variables were used: (1) storm surge level, (2) tidal phases, (3) storm duration and (4) river discharge. One of the outcomes is the probability-function of the hydraulic head as is illustrated in fig 10.
For the determination of the element resistance (strength, stability), initially an attempt was made to distribute probability density functions of loads to the designers in order to enable a full probabilistic design. It became apparent that such a probabilistic methodology did not work for this complex project. Therefore, in most cases a more practical method was applied, based on a conversion of the probabilistic results into design loads and partial safety-factors. In that way the designers could use the standards.

Fig. 9: Fault-tree for barrier collapse

Human failure

All activities with human involvement before and during the barrier-operation were analyzed using a proven technique. Each activity was specified and analyzed on: (1) basic failures, (2) effects of failures and (3) possibilities of retrieval.
With the help of quantitative data from earlier research for these categories of human behaviour, an appropriate estimate of the probability of failure has been made. For some operations suitable measures were recommended to improve the performance (e.g. monitoring by a supporting computer).

Ship collision

The navigation on the New Waterway is very dense. Each year about 80,000 ships pass the barrier-location (10 per hour). Both historical data and reliability analyses showed that a ship collision may be expected once every 20 years. Therefore, a comprehensive study was performed to evaluate the consequences of a ship collision. Special navigational and damage models were developed to quantify the effects of a collision with respect to the functions of the barrier. In order to meet the performance requirements, parts of the barrier had to be adjusted. Also appropriate repair-procedures and provisions were developed.

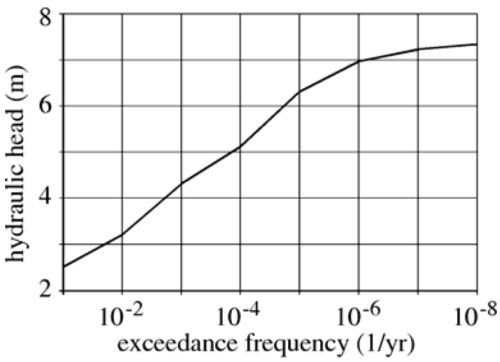


Fig. 10: Probability-function for hydraulic head

7. Model testing

During the tender-phase, an extensive model testing program was performed at Delft Hydraulics Laboratory. In order to investigate hydraulic effects and, in particular, the dynamic behaviour of the main gates under operational conditions, a 1:60 scale model of approximately 3 kilometres of the New Waterway was built. However, as a result of contract negotiations the design was altered significantly.

At that time the gates of the tender-design were provided with 40 sluice openings with a total area of 950 m^2. The sluice openings could be closed by lifting gates. The cross section of the tender-phase barrier concept is shown in fig 11a. The lifting gates had three functions: (1) discharge river water between two tidal high waters, or between two major storm surges following too closely to open the sector gate completely, (2) minimize heads and associated pressure-fluctuations under the gates when the barrier is lowered to the bottom during closure and (3) reduce the maximum hydraulic head over the barrier by allowing water-inlet under certain conditions.
During contract negotiations the design concept was changed. It was decided to skip the sluice openings with the lifting gates, since this reduced the costs significantly. Of the three sluice functions mentioned above, two (discharge water and head reduction) can be realized by lifting the sector gate(s). The time needed to lift the sector gates to the required opening is almost the same as that for opening the lifting gates. However, the decision to skip the sluices implied that a large part of the model testing had to be repeated. In particular the closing and opening phases of the sector gate had to be investigated again, because the earlier model tests were performed with the lifting gates open. The cross section of the barrier without lifting gates is shown in fig 11b.

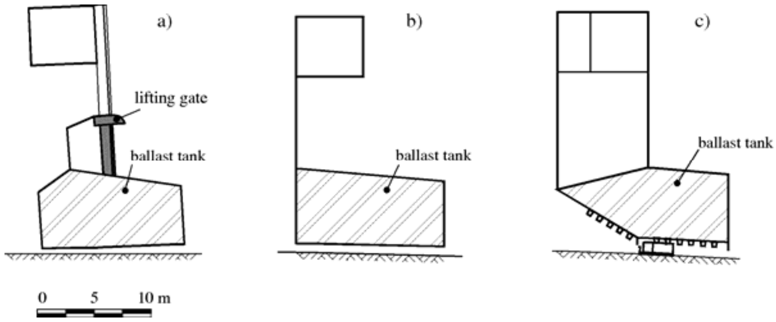


Fig. 11: Cross-sections barrier (a): pre-design (b): contract design (c): present design

It was intended to repeat the tender-phase model tests with the new barrier design. The following hydraulic conditions (design-values) were tested again:

S [m]	ΔH^+ [m]	ΔH^- [m]
7	1.40	0.45
4	2.75	0.70
1	4.00	1.25
0	4.50	0.90

where S is the distance between the barrier and the sill, ΔH^+ is the positive head (water level at the seaside higher than the water level at the riverside) and ΔH^- is the negative head (visa versa).
After re-building the model, positive head tests were performed. When the distance between the sector gate and the sill was between 1 and 4 metres, a strange phenomenon was encountered that had not been recognised in the earlier model tests.
Both gates made an almost perfect out-of-phase cyclic heave movement with a one-minute period. At the same time, downstream of the barrier a transverse standing wave developed between the abutments. The period of the movement perfectly matched the wave-formula: T = L/c = 2*360/12 = 60 seconds, where T = wave period, L = wave length and c = wave celerity. The sector gates followed the downstream standing wave, which can be explained by considering the small (10 seconds) eigenperiod of the gates. The amplitude of the movement could be more than 3 metres. A similar phenomenon was found with the negative head tests. Due to the geometry of the abutments, a pitch-movement was now found, with a period of 30 seconds.
The cause of the phenomenon was not conceived immediately. The first attempts to improve the stability of the barrier can be characterized as trial and error. It was found that the stability improved much by adjusting buoyancy at the seaward side of the barrier.
Unfortunately, when considering pessimistic sediment profiles at the sill, the stability decreased drastically again. In this phase, however, the phenomenon was understood. It can be explained by a rather simple model [2]:

> Assume an infinitesimal water level rise at the downstream side. As a result, the flow decreases due to the decrease of the head. The downstream buoyancy of the gate increases (Archimedes), which results in a greater opening causing an increase of the flow. If the extra flow due to the infinitesimal rise is positive, the initial rise will be followed by an extra rise due to the extra flow. Such a situation can be qualified as unstable.

Following this model, it turned out that the stability of the gates was strongly influenced by the bottom-side geometry of the gates. The model was used to pilot further optimisation of the barrier-geometry. It was a major problem to design a geometry suiting both positive and negative heads. After some minor complications, a solution was achieved that was stable in all operational conditions. The final geometry is shown in fig 11c. The entire operation of re-testing and solving dynamic problems, however, caused a serious delay in the final design (approximately 1 year).

8. Organizational aspects and control of design

The most relevant requirements have been discussed in the previous sections. At the start of the project the barrier concept has been decomposed in 20 sub-systems. The design work needed to develop these sub-systems was described in CTR task units (Cost, Time, Resources) with fixed input and output. This was done with the perception that the precontractual concept would not be subject to significant changes anymore and, hence, the design work would be limited to the engineering of a few details. However, it became apparent that this initial perception of the necessary design work was not correct. In particular it appeared that the large number of requirements together made it difficult to control design activities. Therefore, a few centralized coordination tools are used to link the performance of the storm-surge barrier with the contractual requirements.
The first tool was an overall system analysis in order to observe the behaviour of the system in its environment. Emphasis is laid on operational aspects for both standard and non-standard use.
Given the probabilistic context of the requirements, a full probabilistic design philosophy had been adopted. In this philosophy, the three fault trees as discussed briefly in the previous section play a central role. Using the fault tree technique it is possible to determine the individually required probability of failure for the sub-systems.
Due to the difficult interaction between the prescribed use of the barrier and the complex environment, it is necessary to have appointed specialists to obtain an appropriate distribution of loads. These specialists also have a consultancy task to convert the probabilistic loads into more familiar deterministic design loads and to assist designers with full probabilistic calculations whenever necessary.

Due to the complexity of the barrier system (the sub-systems are strongly interrelated) two coordinating systems are used to monitor interrelations. The first one is the tolerance system which covers all possible fitting problems. The second one is an overall interface control system. Initially the last system did not work satisfactorily due to the strong interrelation of the 20 structural sub-systems.
For this reason, the 20 sub-systems have been grouped into five working clusters. For the formation of the working clusters two criteria were used: (1) minimum number of relations with sub-systems outside the cluster, together with a maximum number of relations within the cluster and (2) an easy change-over of engineering clusters into construction clusters. As the project is rigorously divided into a steel construction part and a civil engineering part, the last criterion was rather predominant in the clustering philosophy.
The effect of the clustering on interface control is positive. Nevertheless, some problems at the interfaces have remained unsolved. This is due to the fact that a cluster leader experiences solving problems within the cluster to be more important than problems at the interfaces with other clusters. In order to solve these remaining interface problems, 4 special target groups have been installed.
The organisational structure is schematically given in fig 12.

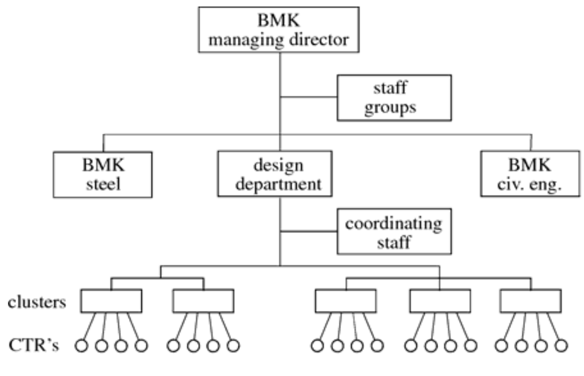


Fig. 12: Organisation of interface control

9. Conclusions

The conceptual design of the storm-surge barrier in the New Waterway was chosen because of the simple load transfer system. The two defined aims in the development process were to use conventional methods of construction and to minimize research efforts. These aims have satisfactory been reached, although a substantial amount of research was needed due to the unacceptable dynamic behaviour of the sector gates in floating

conditions during closure and opening.
This has led to an extensive research programme performed by Delft Hydraulics Laboratories. During these research activities which lasted about 2 years, the exact geometry of the gate could not be fixed. Since the geometry of the barrier has relations to almost all surrounding construction elements, the instability of the changed concept caused severe design problems.
The barrier concept is very complex when considering the number of relations between elements and the number of functions of elements. In consequence, the design work required substantial coordination efforts. Interface management and configuration control have turned out to be key functions in this project. During the project, the organisation structure has been adjusted to improve the coordination and to implement these functions.
The storm-surge barrier project is the first project of this size to be developed under a total QA/QC scheme according to the ISO-9000 standards. QA/QC has proven to be a very learning experience for both the contractor and the client. Implementation of quality management procedures throughout the organisation demands a great deal of effort, especially in showing people that to have a single-point responsibility towards quality means that one has to monitor the quality of one's work. This implies that one should be able to inform management about wavers and deviations without having the feeling that it means that one has done a "bad job".
The tendering procedure, developed by the Ministry of Public Works, has resulted in a conceptual design to be developed and realized with a fixed price plus escalation financial contract. Unexpected phenomena, such as the instability of the gates, have had a large impact on the design process, causing difficulties of both technical and organizational nature. An adequate check on the stability of the changed concept of the gates prior to the contract negotiations could have minimized disruptions in the execution of the project.
After some difficulties of both technical and organisational nature, the project is now well on its way. Due to unforeseen problems, the targeted delivery date has been moved from mid 1996 to mid 1997. In a quality (and budget)-driven project, this is the only realistic escape to prevent quality loss.

10. Literature

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Projet et construction d'un barrage anti-tempête dans le Nieuwe Waterweg, aux Pays-Bas (Specifications techniques et implications contractuelles)

Résumé:
Après le raz-de-marée de 1953 la loi Delta fût lancée pour assurer la protection du Sud-Ouest des Pays-Bas contre les innondations. Cette loi prévoit la fermeture de nombreux bras de mer. De même, la loi tient compte d'une vois ouverte entre la mer et le Nieuwe Waterweg, lequel donne accès à l' important port de Rotterdam (fig. 1 et 2). Les digues le long du Nieuwe Waterweg et ses liaisons fluviales devaient être renforcés. En raison des incidences considérables sur ces régions, caracterisées par une population à densité elevée et un aménagement du territoire complexe, ce programme de renforcement des digues est coûteux.
C'est pourquoi en 1987 L'Administration des traveaux publics et d'aménagement du territoire (Rijkswaterstaat) lança une étude de faisabilité sur la réalisation d'un barrage mobile dans le Nieuwe Waterweg. Parmi les conditions essentielles auxquelles doit satisfaire le projet figurent une reduction déterminé du niveau des eaux du cours inférieur du fleuve et une fréquence de fermeture de 1/5 á 1/10 par an pour maintenir l'accèssibilité du port de Rotterdam. Au niveau de l'emplacement, le fleuve mesure 360 m de large et 17 m de profondeur. En fin de compte le barrage s'avère moins coûteux que le reforcement des digues.
Cinq groupements d'entreprises furent invités à présenter dans les trois mois qui suivent un avantprojet sur la base d'un contrat à prix fixe, comprenant étude et construction. Sur les cinq avantprojets (fig. 4) les deux en arc de cercle furent sélectionnés pour élaborer leurs projets respectiefs à partir de normes fonctionelles déterminées. Finalement le projet fut confié au groupe BMK à la fin de 1989, en raison de la simplicité de la construction et du prix. Le montant du contrat s'éleve à quelque 700 milions de florins (y compris les cinq premières années d'entretien).

Le barrage se compose de deux portes flottantes en arc de cercle, liées à des pivots (fig. 7) de part et d'autre du cours d'eau par des bras en treillis (fig. 5). Les portes sont maintenues à flot pendant la fermeture, puis abaissées par balastage sur un seuil de blocs en béton amenagé au fond du cours d'eau. Le barrage s'ouvre par délestage des portes et parcage dans des bassins creusés de part et d'autre du Nieuwe Waterweg. Ainsi, les portes reposent dans des bassins qui peuvent être fermés et mis à sec.

A cause du grand interêt public, l'Administration a tenu de suivre de près le développement du projet et sa réalisation. Dans le cadre de l'assurance de la qualité, des normes de qualité (ISO-9000) et des procedures d'acceptation sont utilisés.

Les normes de fonctionnement du barrage comprennent des specifications pour la retenue des eaux (vitesse de déplacement, geométrie etc.) et des normes de probabilité d'échec. L'entrepeneur doit donc traduire ces normes abstraites en une structure réelle. L'analyse du risque (fig. 9) et les calculs des probabilitées ont servi à dimensionner les différents éléments structurales et les charges correspondantes à considerer, à partir des normes établis de probabilité d'échec. Pour maîtriser ce projet complexe, caractérisé par de nombreux points de contacts, BMK a bâti un système de controle autour de cinq unités d'étude (fig. 12).

L'avant-projet de BMK comprenait des portes de barrage avec des vannes coulissantes (fig. 11a), qui pouvaient être utilisées pour l'écoulement des eaux entre deux hauts niveaux de l'eau. Même pendant la fermeture, les vannes resteraient ouverts. Pour des raisons économiques, ces vannes ont été enlevées du projet avec la supposition que l'écoulement des eaux pouvait aussi être réalisés en soulevant les portes de leur seuil (fig. 11b). Pendant les recherches de vérification du comportement sur un modèle réduit de 1:60 de Delft Hydraulics il apparut résulter de grandes instabilitées pendant l'abaissement et le soulèvement des portes. Le mouvement était exité par des lames transversales entre les rives. La géométrie des portes y jouait un grand rôle. En combinant un modèle mathématique au modèle réduit de recherche pour ce phénomène, une solution optimale a put être trouvée (fig. 11c). Ces problèmes ont générés un retard d'un an.

Le projet d'étude et de réalisation du barrage dans le Nieuwe Waterweg dure maintenant près de quatre ans et, après quelques problèmes de démarrage, est bien en cours. On prévoit la fin des traveaux vers le milieu de l'anée 1997.